Chapter 7
Water Surface Profiles With Movable Boundaries

Section I
Introduction

7-1. Similarities and Differences Between Fixed and Mobile Bed Computations

The computation of water-surface profiles for flow over a movable boundary differs from fixed bed water-surface profile computations as illustrated in Figures 7-l and 7-2. In both cases a study reach is identified and boundaries are drawn around it to form model limits. Within those model limits, the geometry and loss coefficients are assembled to make a digital model of the study area. A physical analogy at this point is an empty flume.

a. The fixed-bed solution. As can be seen from the basic equations governing steady gradually varied flow over a fixed bed (see Chapter 6), the solution requires that two values be given, usually water discharge and water surface elevation. In mathematical terminology, the flow entering the model and the tailwater elevation are called "boundary conditions." A physical analogy is opening a valve to let water enter a flume and regulating the tailgate so that flow leaves the flume at the desired depth. The boxes in Figure 7-1 depict the solution process by showing the typical hydraulic parameters, water velocity, depth, width and slope, with arrows indicating the sequence of the computations.

b. The mobile-bed solution. The addition of a mobile bed increases the number of processes which must be included in a numerical model. Sediment transport, bed roughness, bed armor, bed surface thickness, bed material sorting, bed porosity, and bed compaction equations are required in addition to the sediment continuity equation which defines the sediment exchange rate between the water column and bed surface. The number of additional equations causes a major increase in complexity. That is not the most significant difference between fixed and mobile bed numerical computations, however. The most important difference is that the cross section shape and bed *n* value become functions of the flow hydraulics. Consequently, a feedback loop is created as illustrated by the arrows in Figure 7-2. The uncertainty about *n* values substantially complicates numerical modeling of mobile boundary problems. There are other major gaps. For example, the bed sorting process which occurs when a mixture of sediment sizes is transported is poorly understood. Also, because sediment is transported primarily in the channel, mobile bed computations must maintain an accurate distribution of flow between the left overbank, channel, and right overbank at each cross section, as well as a history of how the flow arrived at that location in the cross section. It is only necessary to balance energy in a fixed bed computation to solve for the water surface elevation.

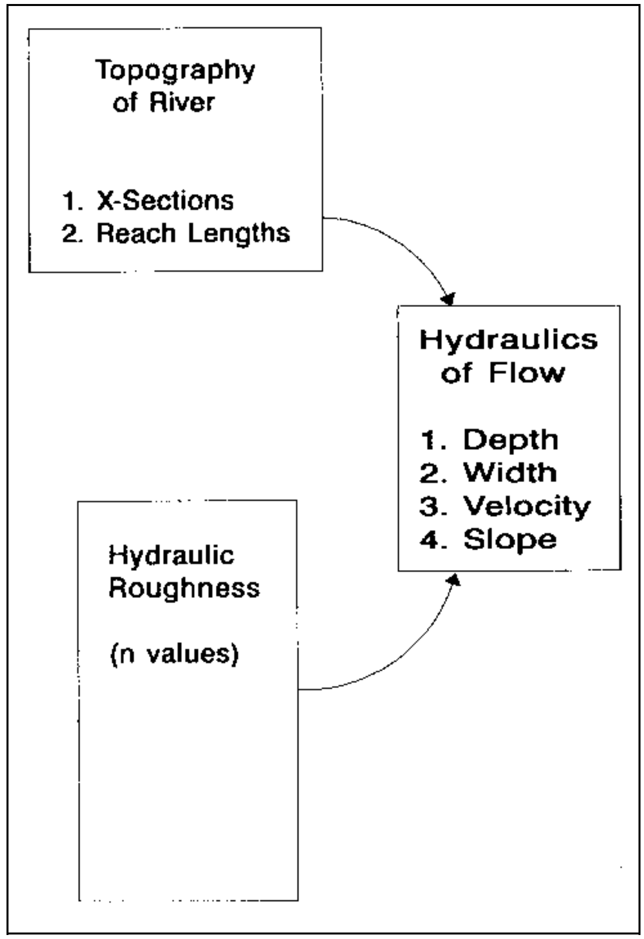

Figure 7-1. Fixed bed model

Section II
Theoretical Basis

7-2. Sediment Transport Functions

Before 1942 much of the work in sediment transport was influenced by DuBoys (1879). He proposed the idea of a

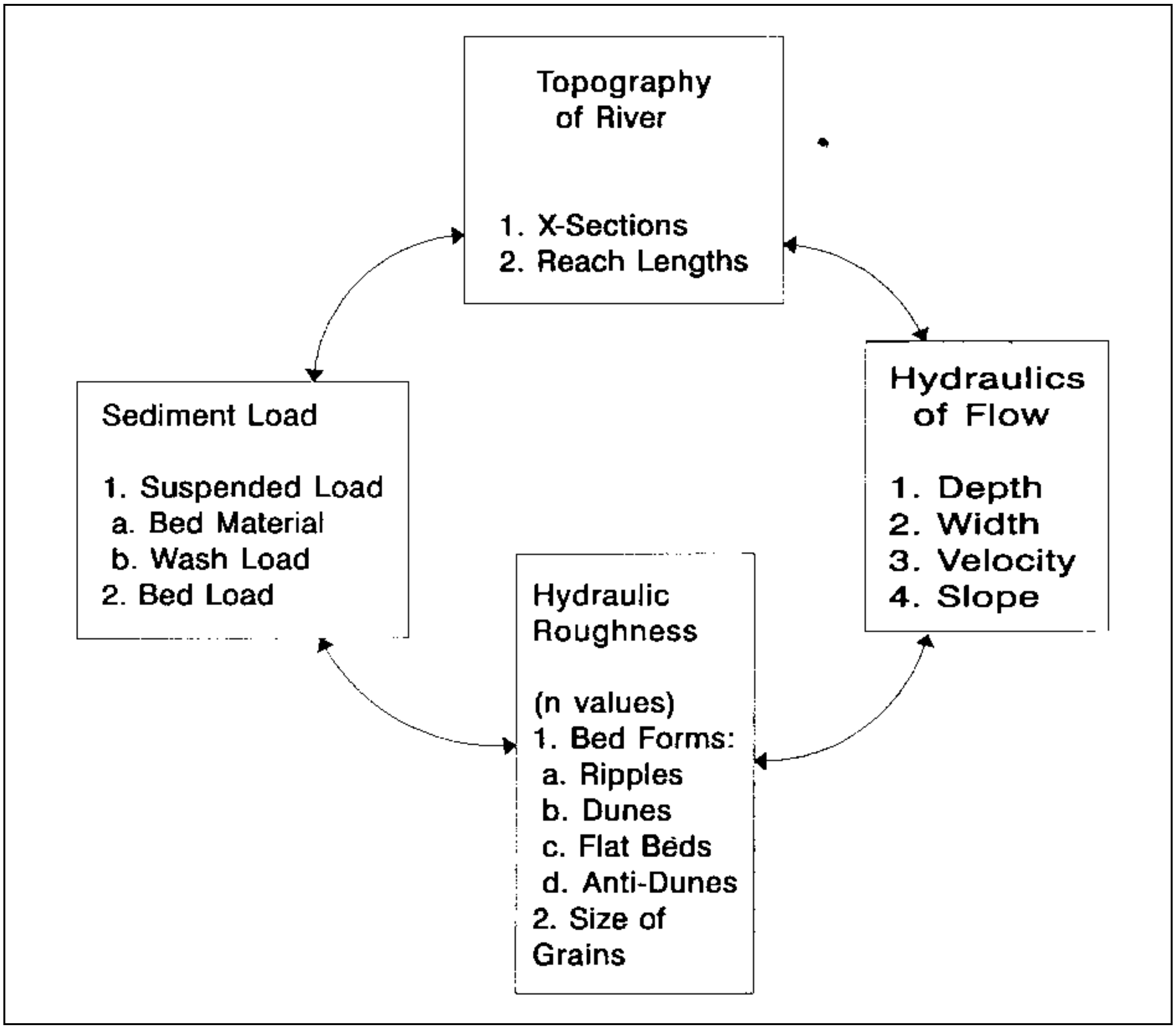

Figure 7-2. Movable bed model

bed shear stress and visualized a process by which the bed material moved in layers. The depth of movement was that required for the velocity to become zero. The DuBoys formula for sediment transport is described in ASCE (1975). A major change in the approach to predicting sediment transport was proposed by Einstein (1942) when he presented a transport formula based on probability concepts in which the grains were assumed to move in steps with the average step length proportional to the sediment grain size. The Einstein Bed-Load Function, Einstein (1950) embodies those concepts.

a. Einstein's concepts. Einstein described bed material transport as follows:

> *The least complicated case of bed-load movement occurs when a bed consists only of uniform sediment. Here, the transport is fully defined by a rate. Whenever the bed consists of a mixture the transport must be given by a rate and a mechanical analysis or by an entire curve of transport against sediment size. For many years this fact was neglected and the assumption was made that the mechanical analysis of transport is identical with that of the bed. This assumption was based on observation of cases where the entire bed mixture moved as a unit. With a larger range of grain diameters in the bed, however, and especially when part of the material composing the bed is of a size that goes into suspension, this assumption becomes untenable. Some examples of this type of transport are given in the flume experiments described on pp. 42-44 of this publication.*

The mechanical analysis of the material in transport is basically different from that of the bed in these experiments. This variation of the mechanical analysis will be described by simply expressing in mathematical form the fact that the motion of a bed particle depends only on the flow and its own ability to move, and not on the motion of any other particles. (Einstein 1950, p. 32)

(1) Einstein's hypothesis that motion of a bed particle depends only on the flow and its own ability to move and not on the motion of any other particles allowed him to describe the equilibrium condition for bed material transport mathematically as two independent processes: deposition and erosion. He proposed an "equilibrium condition," and defined it as the condition existing when "For each unit of time and bed area the same number of a given type and size of particles [are] deposited in the bed as are scoured from it" (Einstein 1950, p. 32).

(2) Although Einstein's work is classic and presents a complete view of the processes of equilibrium sediment transportation, it has been more useful for understanding those processes than for application, partially because of the numerical complexity of the computations. Many other researchers have contributed sediment transport functions - always attempting to develop one which is reliable when compared with a variety of field data. The resulting functions are numerous, yet no single function has proved superior to the others for all conditions. Therefore, the following functional form is presented here to show the importance of various parameters.

$$G = f\,(U,\ d,\ S_e\ ,\ B,\ D_{eff}\ ,\ SG_s\ ,\ G_{sf}\ ,\ D_{si}\ ,\ P_i\ ,\ SG_f\ ,\ T\ ) \quad \text{(Sediment Transport)} \quad (7\text{-}1)$$

where

B = effective width of flow
d = effective depth of flow
D_{eff} = effective particle diameter of the mixture
D_{si} = geometric mean of particle diameters in each size class i
G = total bed material discharge rate in units of weight/time (e.g. tons/day)
G_{sf} = grain shape factor
P_i = fraction of particles of the i^{th} size class that are found in the bed
S_e = slope of energy grade line
SG_f = specific gravity of fluid
SG_s = specific gravity of sediment particles
T = water temperature
U = flow velocity

Of particular interest are the groups of terms: hydraulic parameters (U, d, S_e , B), sediment particle parameters (D_{eff} , SG_s , G_{sf}), sediment mixture parameters (D_{si} , P_i), and fluid properties (SG_f , T).

b. Selection of a sediment transport function. As mentioned above, numerous transport functions have been developed with the aim of computing the rate and size distribution of the transport of bed material, given the hydraulics and bed material gradation (ASCE 1975). As it cannot be stated which one is the "best" to use given a particular situation, the engineer should become familiar with how the functions were derived, what types of data they have been compared to (laboratory flume versus river measurements), and past usage. A recent study (Yang and Wan 1991) rated the accuracy of several transport functions compared with both laboratory and river data and concluded that, for river data, the accuracy in descending order was Yang, Toffaleti, Einstein, Ackers and White, Colby, Laursen, Engelund, and Hansen. It also states that the rating does not guarantee that any particular formula is superior to others under all flow and sediment conditions. Another study (Gomez and Church 1989) favored the formulas of Einstein, Parker, and Ackers-White for gravel bed rivers. An "applicability index" based on river characteristics was developed by Williams and Julien (1989). The WES-SAM (USAEWES 1991) package offers a procedure to aid in the selection. It is based on screening of the various transport functions using information from past studies that compared computed and calculated transport rates and the hydraulic characteristics of the particular stream. Use of such an approach is documented by U.S. Army Corps of Engineers (1990e). The engineer should be aware that different transport functions will probably yield different answers. The impact will most likely be greater on transport rates than on computed geometry changes. Extreme situations, such as mud and debris flows, require different analytic techniques, see U.S. Army Corps of Engineers (1990f) for an example.

c. Numerically modeling the movable boundary problem. Although sediment discharge formulas appear in a numerical model of the movable boundary problem, there are significant differences between the calculations for sediment discharge and those in a mobile boundary sediment movement model. Table 7-1 summarizes those differences. The words "equilibrium" and "nonequilibrium" condition in this table refer to the exchange of sediment particles between the flow field and the bed. Whereas the bed is the only source of sediment to a sediment transport formula, a sediment movement model

Table 7-1
Sediment Tansport versus a Movable Bed Sedimentation model

A. Sediment discharge formulas.	B. Sediment movement models.
A1. Require flow intensity, bed roughness, specific gravity of particles, and bed surface gradation.	B1. All of A1 plus inflowing sediment load, geometry over long distances, bedrock locations, and gradations beneath the bed surface.
A2. Calculate the equilibrium condition.	B2. All of A2 plus calculate changes in bed profile due to nonequilibrium transport.
A3. Functional only for the bed material load.	B3. In the case of sand moving over a gravel bed, models will calculate both the load moving and bed surface gradation required to sustain it. Wash load can be handled in several ways.

should partition the river into reaches so that both the bed and the inflowing sediment load to the reach are sediment sources to the calculations in that reach. Nonequilibrium conditions are common from one reach to the next because sediment movement tends to be highly variable in both rate and particle size distribution. A mobile bed sedimentation numerical model should calculate transport by size class and keep a continuous accounting of the gradation in the stream bed and on its surface.

(1) To have general applicability a numerical sedimentation model must erode, entrain, transport, deposit and consolidate mixtures of sediment particles for the nonequilibrium case. Einstein did not address the nonequilibrium condition, but his "particle exchange" concept was extended for the HEC-6 numerical sediment movement model as described in Section 7-12.

(2) Sediment movement modeling for most engineering studies does not require tracing the motion of individual particles. Rather, it requires calculating the influence of flow intensity on bed particle behavior, subject to particle size and availability. The objective is to calculate changes in the bed surface elevation in response to nonequilibrium sediment conditions and to feed those changes back into the hydraulic calculation of the flow intensity-sediment load parameters. Some questions dealing with sediment quality cannot be fully addressed, however, without tracing the paths and dispersion of the sediment particles.

Section III
Data Requirements

7-3. General Data Requirements

Two types of data are required. One type records the behavior of the prototype. The other is the data required to operate the numerical model. The first is summarized for completeness. The second, which begins with geometry, is presented in more detail. The project area and study area boundaries should be marked on a project map to delineate the area needing data. Show the lateral limits of the study area and the tributaries. Bed profiles from historical surveys in the project area are extremely valuable for determining the historical trends which the model must reconstitute. Aerial photographs and aerial mosaics of the project area are very useful for identifying historical trends in channel width, meander wave length, rate of bank line movement, and land use in the basin. Gage records contain the annual water delivery to the project area and the water yield from it. They are also useful for establishing the hydraulic parameters of depth, velocity, *n*-value, and the trends in stage-discharge curves in, or close to, the study reach. It is important to work with measured data. Do not regard the "extrapolated" portion of a rating curve as measured data. An example of this is shown in Figure 7-3 where the measured flows are less than 1,850 cfs whereas the project formulation flows range up to 16,000 cfs. Be aware that "measured" data is subject to errors as discussed in sections 5-8

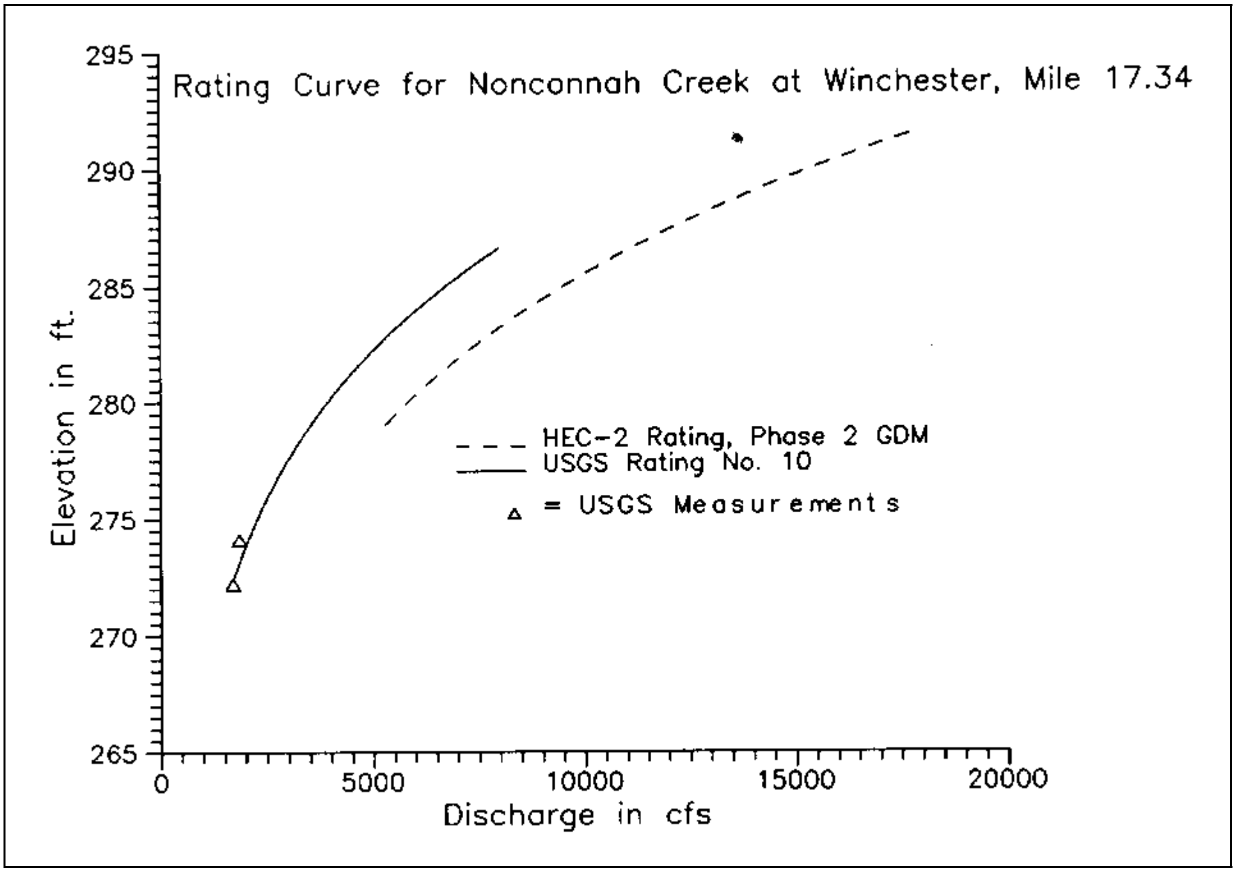

Figure 7-3. Rating curve at a gage

and 6-10. Reconnaissance of the project reach is a valuable aid for determining channel morphology, geometric anomalies, the existence of structures, and sediment characteristics of the channel. Include geotechnical and environmental specialists in a field reconnaissance if possible. Document these observations of the prototype in project reports. View as much of the prototype as is feasible and not just at bridge crossings. Hydraulic data such as measured water surface profiles, velocities, and flood limits in the study reach are extremely valuable. Local agencies, newspapers, and residents along the stream are valuable sources of information that can supplement field measurements.

7-4. Geometric Data

Mobile bed calculations attempt to determine the water surface and bed surface elevations as they change over time. It is necessary to prescribe the initial geometry. After that, computations aggrade or degrade the cross sections in response to mobile bed theory. The cross sections never change locations.

a. Cross sections.

(1) As in fixed bed calculations, it is important to locate the cross sections so they model the channel contractions and expansions. It is particularly important in mobile boundary modeling to also recognize and set conveyance limits. That is, when flow does not expand to the lateral extent of a cross section in the prototype, conveyance limits should be set in the model.

(2) There is no established maximum spacing for cross sections; it depends on both study needs and accuracy requirements related to the particular numerical model being used. Some studies have required distances as short as a fraction of the river width. Others have successfully used sections spaced 10-20 miles apart. The objective is to develop data that will reconstitute the historical response of the streambed profile and capture

key features of the flow and the boundary movement. The usual approach is to start with the same geometry that was developed for fixed bed calculations. Note that, as most fixed bed data sets are prepared to analyze flood flows, they may be biased towards constrictions such as bridges and deficient of reach-typical sections that are important for long term river behavior. There may also be cases when some of these cross sections must be eliminated from the data set to preserve model behavior, such as at deep bends or junctions where the shape is molded by turbulence and not one-dimensional sediment transport, but those are usually exceptions.

b. River mile. Show the cross sections on a map, as in Figure 7-4, for future reference. Use of river mile as the cross section identification number is recommended. It is much easier to use or modify old data if the cross sections are referenced by river mile rather than an arbitrary section number.

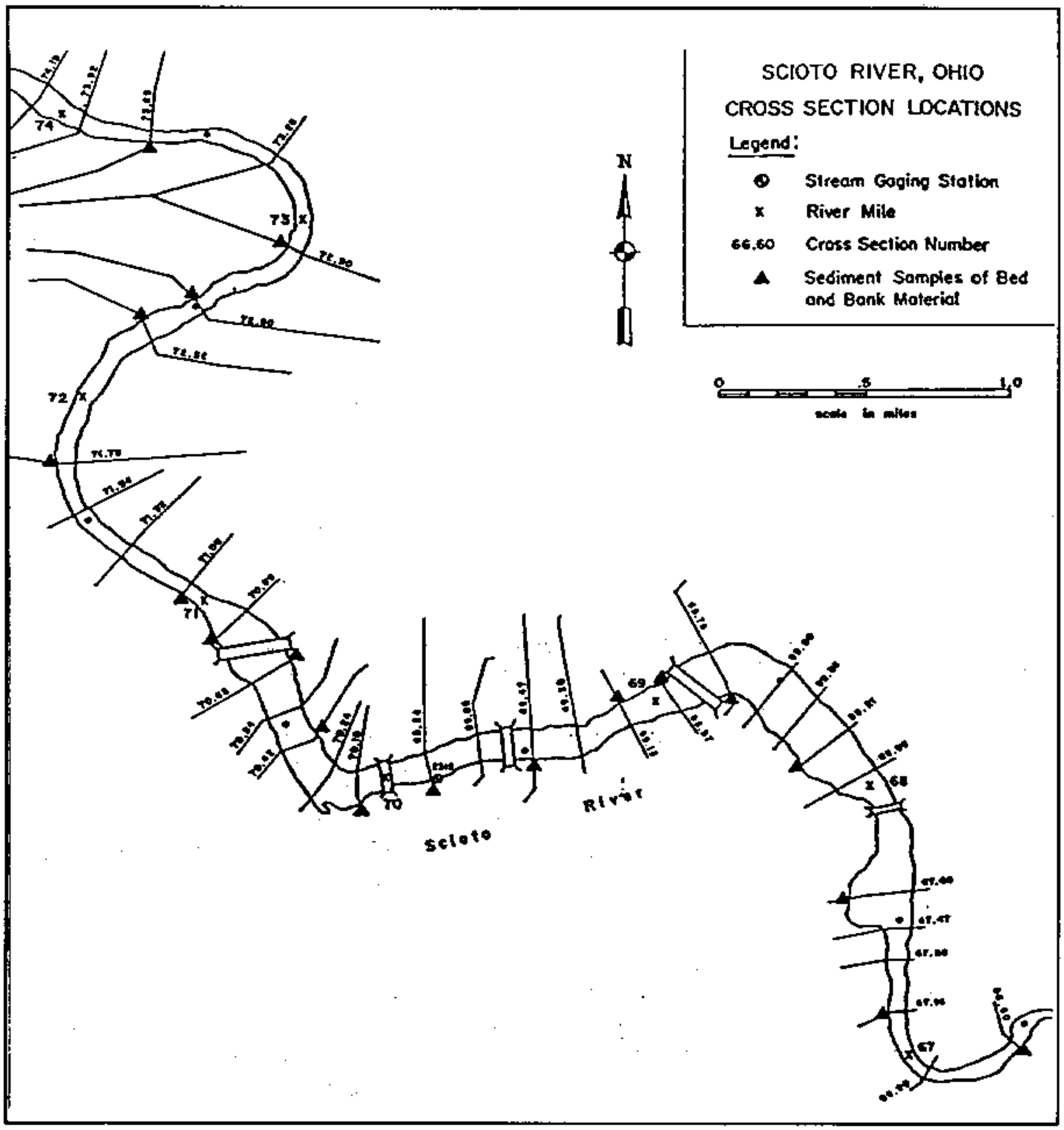

Figure 7-4. Cross section locations

7-5. Bed Sediment Data

The bed sediment reservoir is the space in the bed of the stream from which sediment can be eroded or on to which it can be deposited. This reservoir occupies the entire width of the channel, and in some cases, the width of the overbank also. It might have a very small depth, however, as in the case of a rock outcrop.

a. Gradation of the bed sediment reservoir. It is also necessary to prescribe the gradation of sediment in the bed sediment reservoir.

b. Conditions data. The section on "Boundary Conditions Data" (7-6) provides suggestions for selecting sample locations for use in calculating an inflowing sand and gravel discharge rate. This section gives suggestions for selecting locations that also describe development of the armor layer to resist erosion.

(1) For example, in one study two samples were taken in the dry at each of 27 cross sections spaced over a 20 mile reach of the creek. One was from near the water's edge and the other was from the point bar deposits, about half the distance to the bank. These samples were sieved separately and the resulting gradations plotted; see Figures 7-5 and 7-6.

(2) Results from the water's edge samples were used to test for erosion because they were coarser than themid bar samples. The midbar samples were used to test for transport rates.

7-6. Boundary Conditions Data

Four types of data are included in this category: inflowing water discharges, inflowing sediment concentrations, inflowing sediment sizes, and elevation of the water surface at the outflow boundary.

a. Water inflows. Although an instantaneous water discharge (e.g. a flood peak) may be of interest, it is not sufficient for movable bed analysis because time is a variable in the governing equations and sediment volumes rather than instantaneous rates of movement create channel changes. Consequently, a water discharge hydrograph must be developed. This step can involve manipulations of measured flows, or it can require a calculation of the runoff hydrograph. Historical flows are needed to reconstitute behavior observed in the river, and future flows are needed to forecast the future stream bed profile.

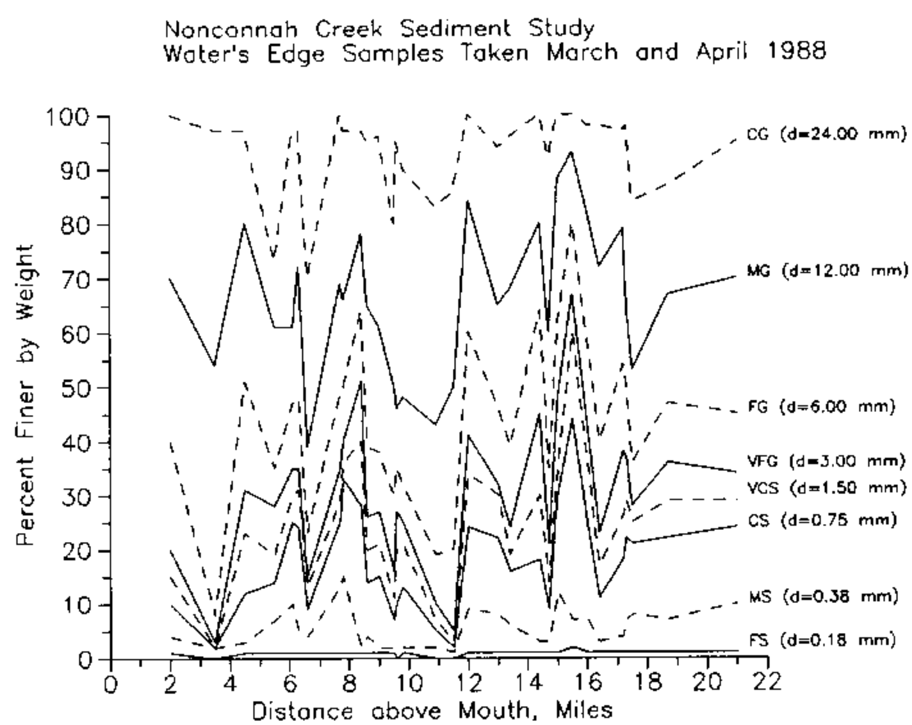

Figure 7-5. Bed surface gradation based on water edge samples

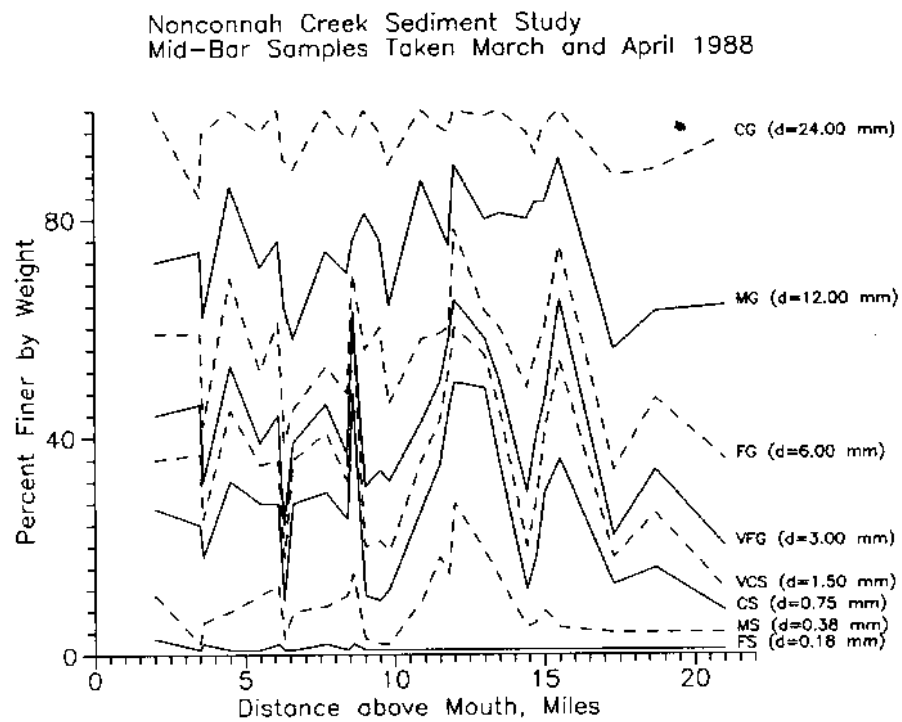

Figure 7-6. Bed surface gradation based on midbar samples

(1) The length of the hydrograph period is important. Trends of a tenth of a foot per year of change in bed elevation become significant during a 50- or 100-year project life. A long period hydrograph can become a computational burden. In some cases, data compression techniques may be useful. As an example, Figure 7-7 shows how a year of mean daily flows might be represented by fewer discharges of longer duration.

(2) Tributaries are lateral inflow boundary conditions. They should be located, identified, and grouped as required to define water and sediment distributions. The locations should be shown on the map of the cross section locations. It is important that the water and sediment inflows from all gaged and ungaged areas within the study reach be included. A water balance should be performed for the study period. Keep in mind that a 10 percent increase in water discharge may result in a 20 percent increase in bed material transport capacity. Inflows from ungaged areas must be developed. Drainage area ratios may be used in some cases; in others, however, use or development of a hydrologic model of the basin may be necessary. Document how inflows were determined for those tributaries that were not included in the analysis as individual channels.

b. Sediment inflows. The second and third boundary conditions are the inflowing sediment concentration and the fraction of that concentration in each particle size class.

(1) Inflowing sediment concentrations. Occasionally suspended sediment concentration measurements, expressed as milligrams per liter, are available. These are usually plotted against water discharge and often exhibit very little correlation with the discharge; however, use of such graphs is encouraged when developing or extrapolating the inflowing sediment data. As the analysis proceeds, it is desirable in most situations to convert the concentrations to sediment discharge in tons/day and to express that as a function of water discharge as shown in Figure 7-8. A scatter of about 1 log cycle is common in such graphs. The scatter is smaller than on the concentration plot because water discharge is being plotted on both axes. The scatter may result from seasonal effects (e.g., vegetation and fires), random measurement errors, changes in the watershed or hydrology during the measurement period, or other sources. The analyst should carefully examine these data and attempt to understand the shape and variance of the relationship.

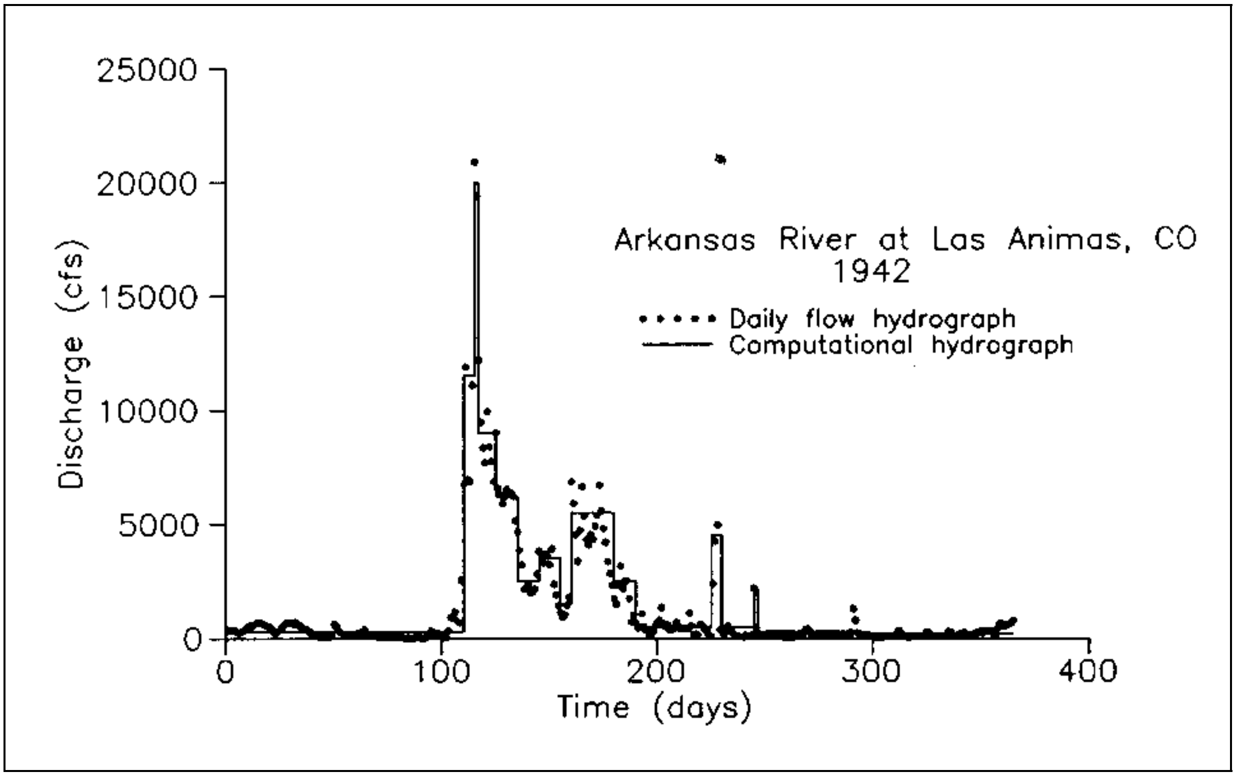

Figure 7-7. Water discharge histograph

(2) Grain size classes. The total sediment discharge should be partitioned into size classes for the mobile bed computations. Table 7-2 shows a procedure developed for the Clearwater River at Lewiston, Idaho. Figure 7-9 is the graph of that data set. Note that, due to the availability of various size fractions in the bed and the suspended load gradation for a given flow, the transport rate does not necessarily decrease with increasing particle size. This phenomenon occurs primarily at low flows and may, therefore, be of little consequence to the overall stream behavior.

(3) Calculating sediment inflow with transport theory. When no suspended sediment measurements are available, the inflowing sediment boundary condition must be calculated. That is possible for sand and gravel using mobile bed hydraulics and sediment transport theory. There is no comparable theory for the wash load inflow. When making a calculation for the boundary condition, select the reach of channel very carefully. It should be one approaching the project which has a slope, velocity, width and depth typical of the hydraulics which are transporting the sediment into the project reach. It should also have a bed surface that is in equilibrium with the sand and gravel discharge being transported by the flow. Having located such a reach, sample the bed surface over a distance of several times the channel width. Focus on point bars or alternate bars rather than the thalweg of the cross section. Measure the geometry of that reach. Make the calculation by particle size for the full range of water discharges in the study plan.

(4) Bed material sampling. Figure 7-10 illustrates a typical bed sediment gradation pattern on a point bar. Use such information to determine where to sample to get the bed gradation for a sediment transport calculation. Note that, although the typical grain sizes found on the bar surface form a pattern from coarse to fine, there is no one location which always captures the precise distribution which will represent the entire range of processes in the prototype. The bed gradation governs the calculated sediment discharge. For example, the rate of transport increases exponentially as the grain size decreases (Figure 7-11). There is no simple rule for locating samples. The general rule is "always seek representative samples." That is, very carefully select sampling locations and avoid anomalies which would bias either the calculated sediment discharge or the calculated bed stability against erosion. Samples taken near structures such as bridges

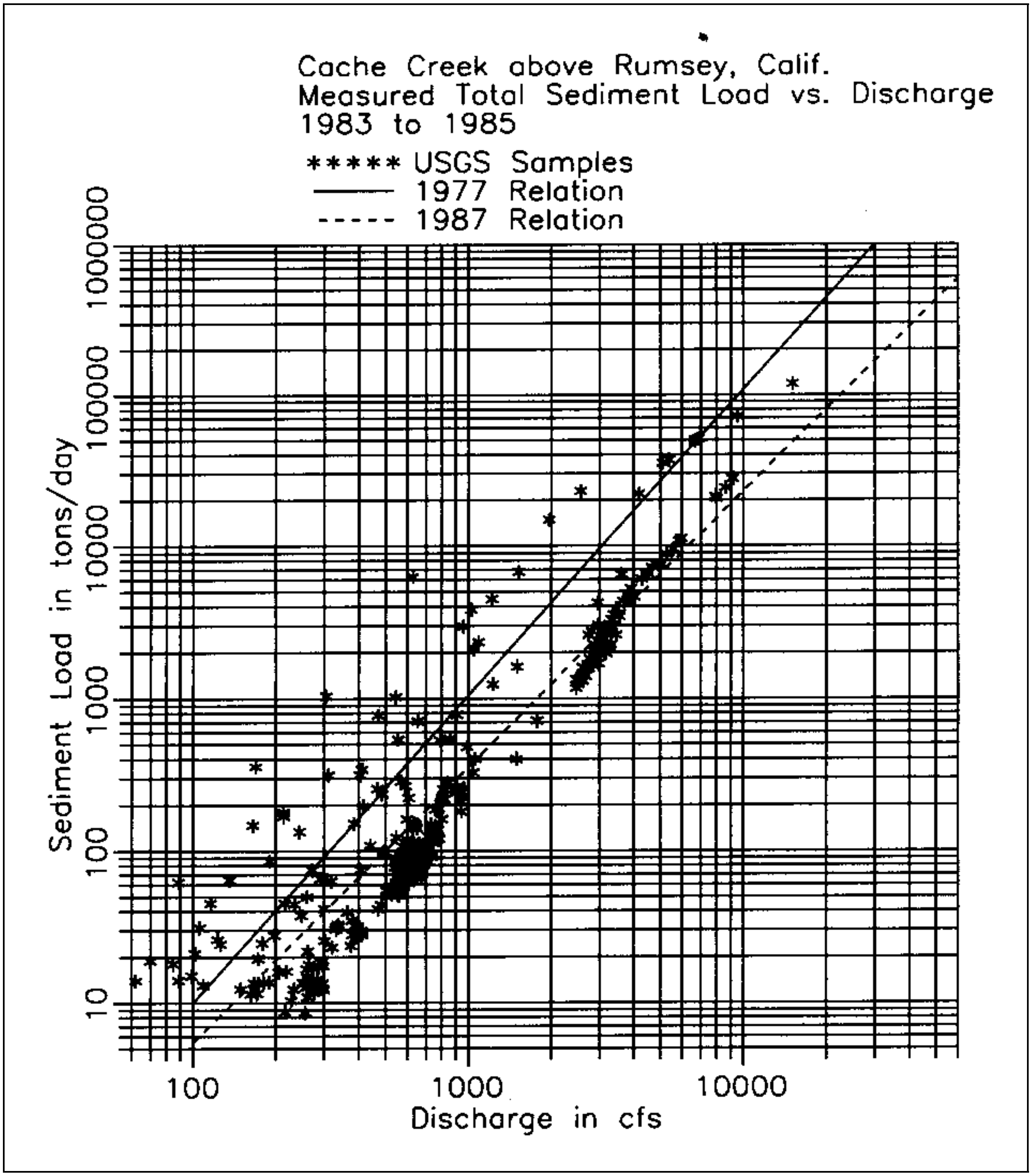

Figure 7-8. Sediment-discharge rating curve

Table 7-2
Distribution of Sediment Load by Grain Size Class

Water discharge: 35,000 cfs

Total Bed Load, tons/day. 130
Total Susp. Load, tons/day. 1,500
Total Sediment Load. 1,630

Grain Size Diameter mm	Classification	Percent Bed Load	Bed Load tons/day	Percent Suspended Load	Suspended Load tons/day	Total Load Column (4) +(6) tons/day
(1)	(2)	(3)	(4)	(5)	(6)	(7)
<.0625	silt & clay	0.04	0.05	54	810	810
0.0625-.125	VFS	0.10	0.13	10	150	150
0.125-.250	FS	2.75	4.00	13	195	199
0.250-.500	MS	16.15	21.00	19	285	306
0.500-1	CS	13.28	17.00	4	60	77
1-2	VCS	1.19	2.00			2
2-4	VFG	1.00	1.00			1
4-8	FG	1.41	2.00			2
8-16	MG	2.34	3.00			3
16-32	CG	6.33	8.00			8
32-64	VCG	23.38	30.00			30
>64	cobbles & larger	32.03	42.00			42
TOTAL		100.0	130.18	100.0	1,500	1,630

Notes:
1. The distribution of sizes in the bed load is usually computed using a bed load transport function and field samples of bed material gradation. The bed load rate is rarely measured and may have to be computed.
2. The suspended load and its gradation can be obtained from field measurements.

will rarely be representative of reach transport characteristics.

(5) Sediment inflow from tributaries. The sediment inflow from tributaries is more difficult to establish than it is for the main stem because there is usually less data. The recourse is to assess each tributary during the site reconnaissance. For example, look for a delta at the mouth of the tributary. Look for channel bed scour or deposition along the lower end of the tributary. Look for drop structures or other controls that would aid in stabilizing a tributary. Look for significant deposits if the tributaries have concrete lining. These observations will help guide the development of tributary sediment discharges.

c. Tailwater elevation. The final boundary condition specifies the water surface elevation at the downstream end of the study reach. It is referred to as a tailwater elevation because it serves the same purpose as a tailgate on a physical model. It can be a stage-discharge rating curve (Figure 7-3); or it can be a stage hydrograph. The rating curve can be calculated by normal depth if the boundary is in a reach where friction is the control and the water surface slope is approximately constant for the full range of discharges. When a backwater condition exists, such as at the mouth of a tributary or in a reservoir, then use a stage hydrograph as the boundary condition. Be sure it covers the same period of time as the inflow hydrographs.

d. Boundary condition changes over time. The above discussion assumes that the inflowing sediment load curves and their particle size distributions, as well as the tailwater rating curve, will not change in the future. That assumption should be justified for each project or appropriate modifications made to the study procedure and numerical model application.

7-7. Data Sources

a. General. The data that will be needed for the study may come from office files, other federal agencies, state or local agencies, universities, consultants, the team making the field reconnaissance of the project site and

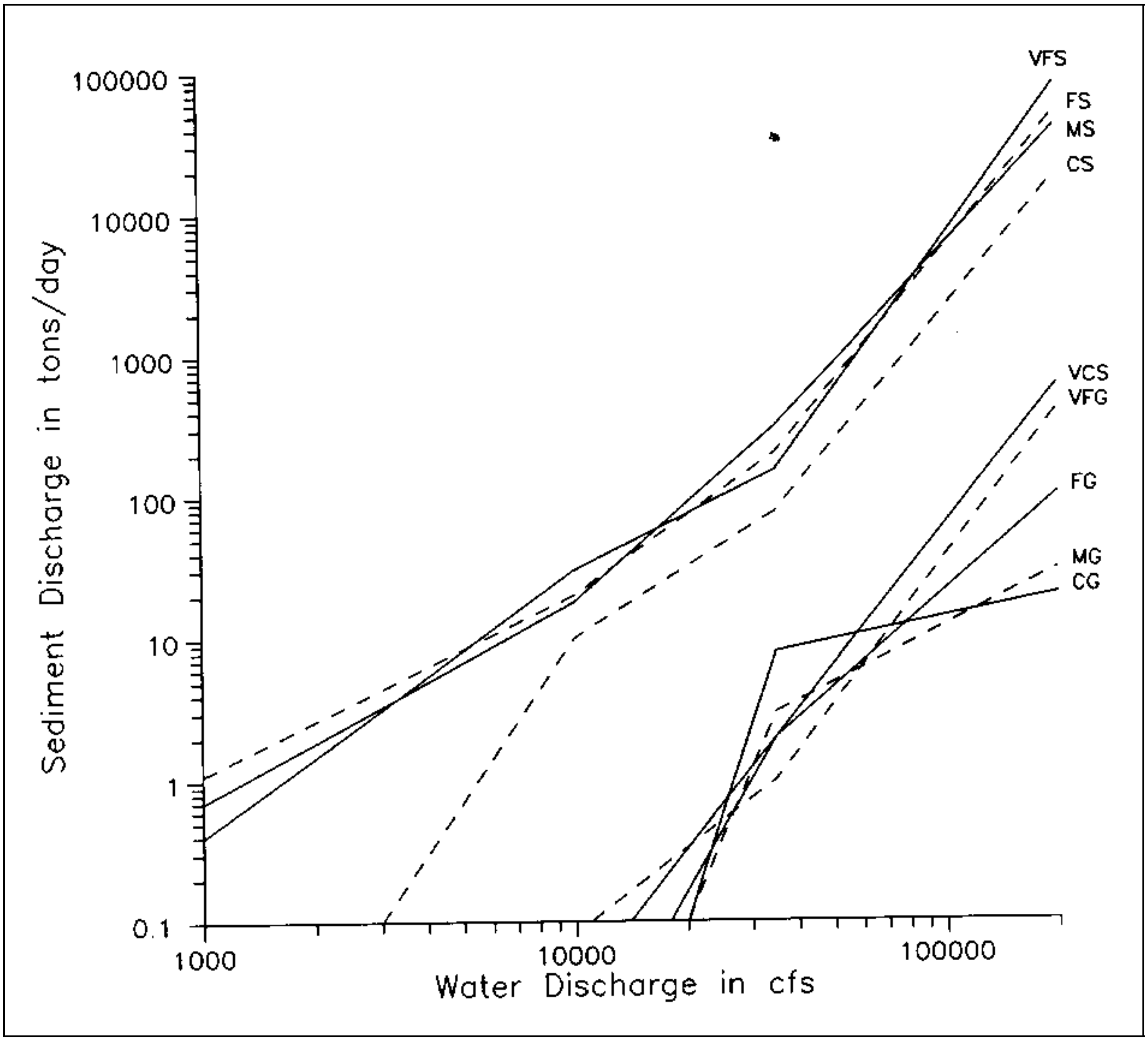

Figure 7-9. Sediment load curves

study reach, and surveys initiated specifically for the study.

b. U. S. Geological Survey (USGS). USGS topographic maps and mean daily discharges are used routinely in hydraulic and hydrology studies and are also common data sources for sediment studies. Mean daily flows, however, are often not adequate for sediment studies. Data for intervals less than one day or stage-hydrographs for specific events, if needed, can be obtained from strip-chart stage recordings that are available by special request. It may be preferable to use USGS discharge-duration tables rather than developing such in house; these are available from the state office of the USGS. Water quality data sometimes include suspended sediment concentrations and grain size distributions. Published daily maximum and minimum sediment discharges for each year and for the period of record are available as are periodic measurements of particle size gradations for bed sediments.

c. National Weather Service (NWS). There are cases where mean daily runoff can be calculated directly from rainfall records and expressed as a flow-duration curve without detailed hydrologic routing. In those cases, use the rainfall data published monthly by the National Weather Service for each state. Hourly and daily rainfall data, depending on the station, are readily accessible. Shorter interval or period-of-record rainfall data can be

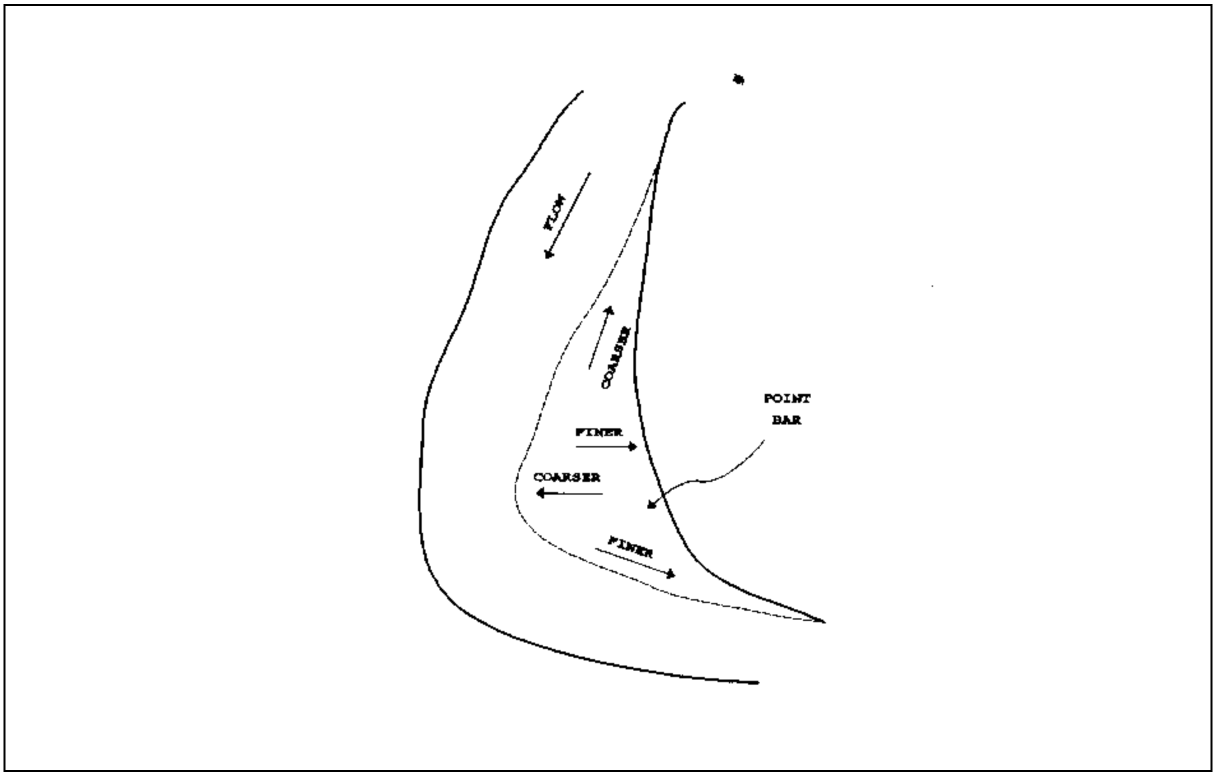

Figure 7-10. Gradation pattern on a bar

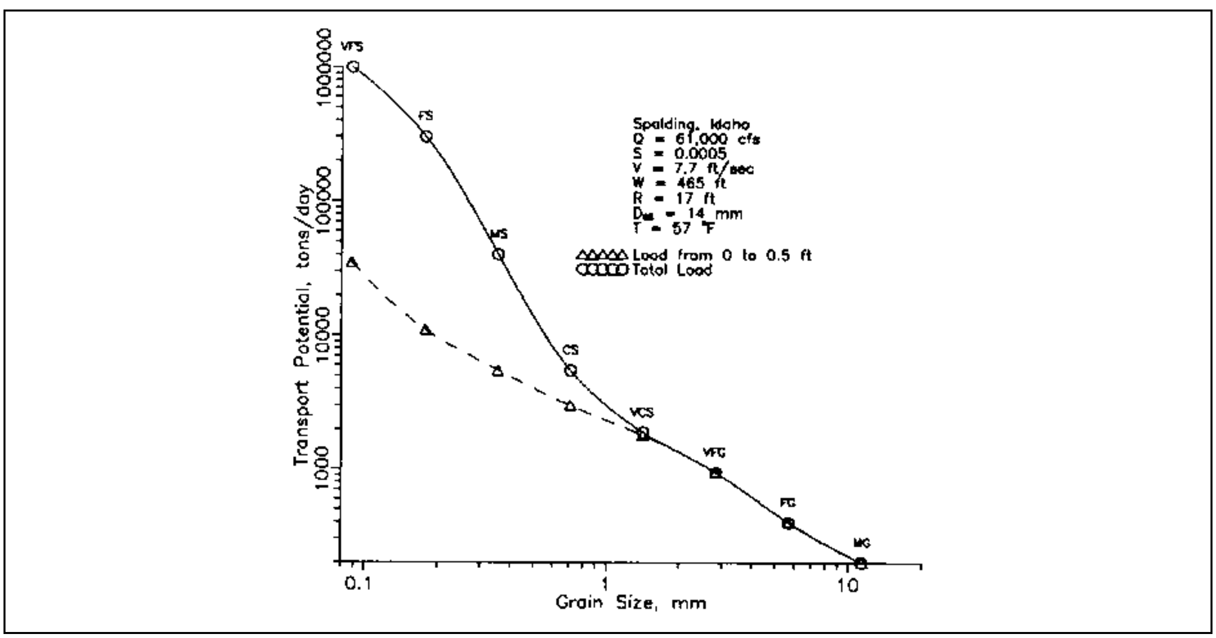

Figure 7-11. Variation of sediment transport with grain size

obtained from the NWS National Climatic Center at Asheville, North Carolina.

d. Soil Conservation Service (SCS). The local SCS office is a good point of contact for historic land use information, estimates of future land use, land surface erosion, and sediment yield. They have soil maps, ground cover maps, and aerial photographs which can be used as aids to estimate sediment yield. Input data for the Universal Soil Loss Equation is available for much of the United States. The SCS also updates reservoir sedimentation reports for hundreds of reservoirs throughout the country every 5 years, providing a valuable source of measured sediment data.

e. Agricultural Stabilization and Conservation Service (ASCS). This agency of the Department of Agriculture accumulates aerial photography of crop lands for allotment purposes. Those photographs include the streams crossing those lands and are therefore extremely valuable for establishing historical channel behavior because overflights are made periodically.

f. Corps of Engineers. Because the Corps gathers discharge data for operation of existing projects and for those being studied for possible construction, considerable data for a particular study area may already exist. The Corps has acquired considerable survey data, aerial and ground photography, and channel cross sections in connection with floodplain information studies. Corps laboratories have expertise and methods to assist in development of digital models.

g. State agencies. A number of states have climatologic, hydrologic, and sediment data collection programs. Topographic data, drainage areas, stream lengths, slopes, ground cover, travel, and times are often available.

h. Local agencies, universities, consultants, businesses and residents. Land use planning data can normally be obtained from local planning agencies. Cross section and topographic mapping data are also often available. Local agencies and local residents have in their verbal and photographic descriptions of changes in the area over time, information that is most valuable to the engineer. This source may include descriptions of channel changes associated with large flood events, incidents of caving banks, significant land use changes and when these changes occurred, records of channel clearing/dredging operations and other information. Newspapers and individuals who use rivers and streams for their livelihood are likewise valuable sources for data.

7-8. Data and Profile Accuracy

Agreement between calculated and measured water surface elevations of ± 0.5 foot is usually satisfactory for mobile boundary studies of natural rivers. Profiles of the computed average bed elevation may not correlate well with the prototype, but cross-sectional area changes should match prototype behavior.

Section IV
Model Confirmation and Utilization

7-9. Model Performance

Prior to using a numerical model for the analysis of a project, the model's performance needs to be confirmed. Ideally this consists of a split record test: selection (or calibration) of coefficients and verification of coefficients. The selection phase is intended to allow values for the coefficients to be chosen and adjusted so that the computed results reproduce field measurements within an acceptable error range. Computed results should be compared with measurements from the prototype to identify data deficiencies or physically unrealistic coefficients. Coefficients should then be adjusted as necessary, within the bounds associated with their uncertainty, to improve the agreement between observed and calculated values. Model adjustment does not imply the use of physically unrealistic coefficients to force a poorly conceived model to exactly match prototype measurements. If a discrepancy between model results and prototype data persists, then either there is something wrong with the model representation of the dominant physical processes (a model deficiency as a result of limiting assumptions), there is a deficiency in the representation of field data as model input (an application error), and/or there is something wrong with the measured data (a data deficiency). Therefore, if model calibration cannot be accomplished through the use of physically realistic values of the coefficients, the measured prototype data should be checked for possible errors and the numerical model (input data, basic equations, and solution algorithms) examined.

a. Model adjustment. Model adjustment is the process of data modification that produces simulation results that are in acceptable agreement with the prototype behavior. Adjustment consists of the selection of values for fixed and movable bed coefficients, and application of the art of transforming three-dimensional prototype measurements into "representative" one-dimensional data. Fixed bed coefficients are Manning's *n* values which do not depend on the characteristics of the movable boundary, coefficients of contraction and expansion, and ineffective flow area delineation. Movable bed coefficients are *n* values for the movable bed, which may depend on the rate of sediment transport. Development of representative data for one-dimensional computations is not done by simply averaging a collection of samples. For geometry, it is the selection of cross sections which will yield a one-dimensional approximation of hydraulic parameters that reconstitutes prototype values so that water and sediment movement in the model mimics that in the prototype. For sediment, it is the selection of bed sediment gradations, inflowing sediment loads and the fraction of sediment in each size class of those loads that reflect the dominant prototype processes.

(1) Manning's *n* values. The most credible method for determining *n* values for flood flows is to reconstitute measured high water profiles from historic floods. Another method is to reconstitute measured gage records. When there are no reliable field measurements the recourse is to use movable boundary roughness predictors for the movable bed portion of the cross section (Brownlie 1981, Limerinos 1970) and calibrated photographs (Barnes 1967, Chow 1959) for the overbank and fixed bed portions. Document prototyped conditions with photographs during the field reconnaissance.

(2) Contraction and expansion losses. Information on contraction and expansion losses is more sparse than for *n* values. King and Brater (1963) give values of 0.5 and 1.0, respectively, for a sudden change in area accompanied by sharp corners, and values of 0.05 and 0.10 for the most efficient transitions. Design values of 0.1 and 0.2 are suggested. They cite Hinds (1928) as their reference. Values often cited by the U.S. Army Corps of Engineers (1990b) are 0.1 and 0.3, contraction and expansion respectively, for gradual transitions.

(3) Representative data. Developing a one-dimensional representation of a three-dimensional open channel flow problem is an art. It requires one to visualize the three-dimensional flow lines in the actual problem and translate that image into a one-dimensional description. This step will often require several iterations to arrive at an acceptable representation. A useful approach is to "creep" up on a solution by first running a fixed bed simulation then adding sediment.

b. Initial tests.

(1) Steady flow, fixed-bed tests. Start with a steady state discharge of about bank-full. In a regime channel this is expected to be about the 2-year flood peak discharge. Ascertain that the model is producing acceptable hydraulic results by not only reconstituting the water surface profile, but also by plotting and examining the water velocity, depth, width and slope profiles. This test will often reveal width increases between cross sections that are greater than the expansion rate of the fluid and, therefore, require conveyance limits. Computed velocities at extremely deep bend sections may occasionally not be representative of sediment transport around the bend; one recourse is to eliminate those sections from the model. The results from running this discharge will also give some insight into how close the existing channel is to a "normal regime." That is, if there is overbank flow, justify that it does indeed occur in the prototype and is not just a "numerical problem" because in a regime channel the bank-full discharge is considered to be about the 2-year flood peak. It is useful to repeat this steady state, fixed bed, test for the maximum water discharge to be used in the project formulation before moving on to the movable bed tests. The key parameters to observe are water surface elevations, flow distribution between channel and overbanks, and velocities. Each study is unique, however, and one should regard the contents of this paragraph as suggestions that illustrate the analysis process and not a complete checklist.

(2) Steady flow, movable bed tests. It is useful to evaluate the model performance for the 2-year flood peak with a movable bed. Again, if the channel is near regime, this should be about a dominant discharge and result in very little aggradation or degradation. Before focusing on sediment transport, however, demonstrate that the Manning's *n* value for the channel is appropriate for a movable boundary. Make whatever adjustments are necessary to ensure that the *n* value for the stream bed portion of the cross section is in reasonable agreement with that obtained from bed roughness predictors. Also, the sediment transport rate will usually be higher at the beginning of the simulation than later because there is normally an abundance of fines in the bed samples which will be flushed out of the system as the bed layers are formed. A physical analogy is starting water to flow down a newly constructed ditch. It is important to balance the sizes in the inflowing bed material sediment load with transport potential and bed gradation. The scatter in measured data is usually sufficiently great to allow smoothing, but the adopted curves should remain within that scatter.

c. Consequences of inaccurate n values. In fixed bed hydraulics, a range of *n* values is typically chosen. The low end of that range provides velocities for riprap design, and the high end provides the water surface profile for flood protection. In movable bed studies such an approach is usually not satisfactory because of the feedback linkage between sediment transport and hydraulic roughness. Use of Manning's *n* values which do not conform with that linkage can result in either too much degradation or too much aggradation.

d. Verification process. The model adjustment process is to ensure that the model will reconstitute the trends which have been observed in the prototype. The second step, the verification process, is to change boundary conditions and rerun the model without changing the coefficients. This step establishes whether or not the coefficients which were selected in the first step will also describe the prototype behavior when applied to events not used in their selection. Change the inflowing sediment load as necessary to correspond with that during the time period selected for verification. Start with steady state data and progress to a hydrograph of flows.

(1) It is important to base the evaluation of model performance on those processes which will be used in decision making. These usually include the water surface profiles, flow distributions between channel and overbanks, water velocities, changes in cross-sectional area, sediment discharge passing each cross section, and accumulated sediment load by size class passing each cross section. A one-dimensional model may not precisely reconstitute thalweg elevations because the thalweg behavior is a three-dimensional process. Therefore, use cross-sectional end area changes or other measures rather than thalweg elevation in the verification test. Three types of graphs should be plotted to show verification results. The first is "variable versus elevation." An example, the comparison of calculated stages with the observed rating curve, is shown in Figure 7-12. The second graph is "variable versus distance" at a specific time as illustrated by the water surface and bed surface profiles in Figure 7-13. The third is "variable versus time" at selected cross sections along the study reach as shown in Figure 7-14.

(2) The verification period used may be several years long. If so, select only a few key values per year to plot. Plot the calculated water surface elevations at all gages in the study area as well as the observed elevations that occurred at the same time. Model performance may be quantified by computing the mean of the absolute values of error. Of course, the lower the mean value of

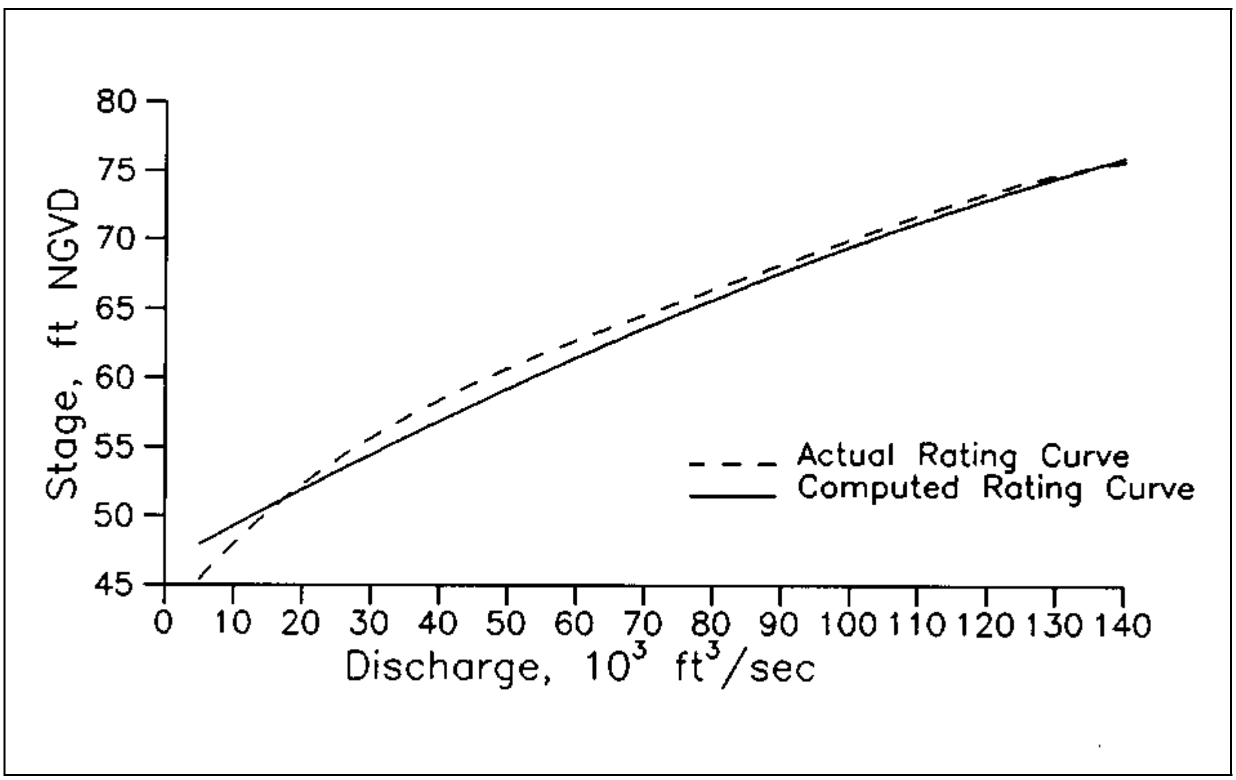

Figure 7-12. Reconstituting the stage-discharge rating curve

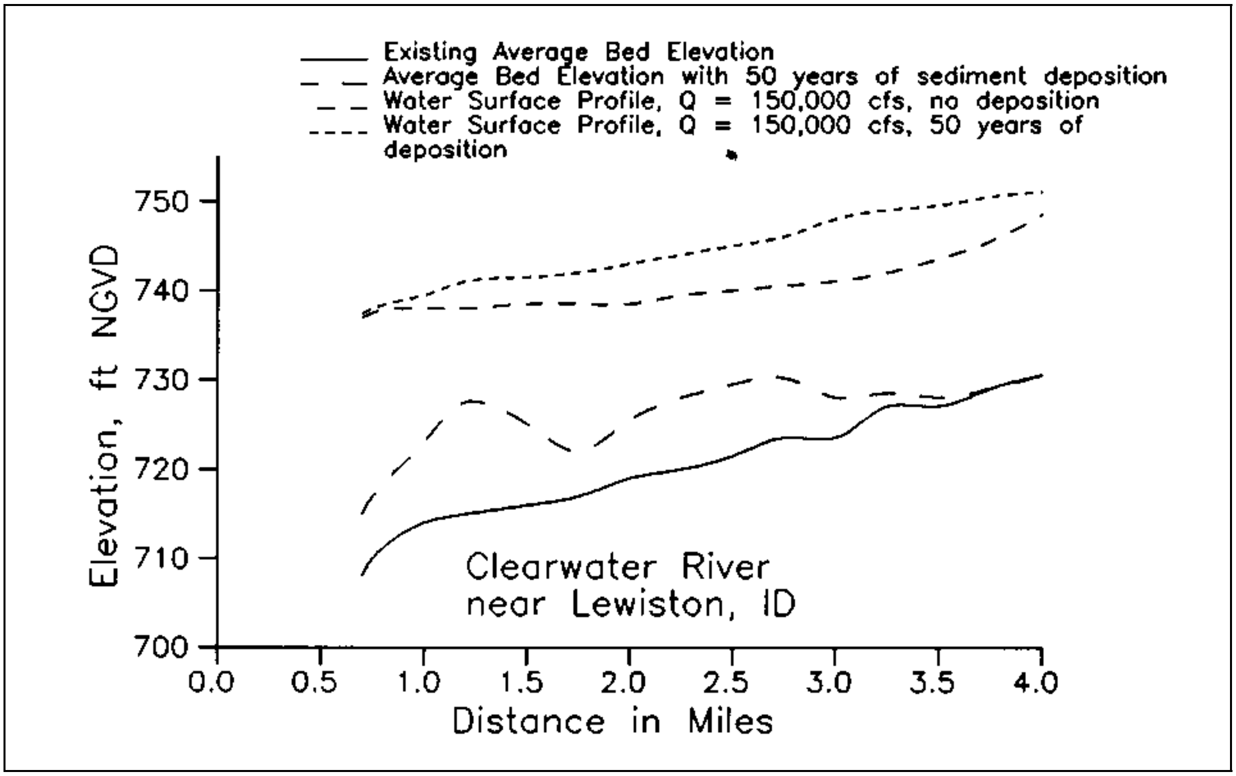

Figure 7-13. Water surface and bed surface profiles

error, the better the performance. Unfortunately, performance quality is defined by problem-specific characteristics and will probably differ from problem-to-problem. Good engineering judgment should be used to determine when the model's performance is satisfactory or requires additional adjustment.

e. Correcting model performance. If the calculated results do not follow the observed trends, take the following steps. First, plot the active bed gradation from cross sections at and downstream from inflow points using results from near the end of the hydrograph along with a bed gradation curve from field measurements. If the model is reproducing the dominant processes in the prototype, the key parameters should match reasonably well. The following suggestions illustrate the thought process that should occur when there is an unacceptable deviation.

(1) First, position the upstream boundary of the model in a reach of the river which is stable, and be sure the model exhibits that stability. That means that cross sections near the upstream end of the reach should neither significantly erode nor deposit. Attend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse that direction for sediment problems. Do not worry about scour or deposition at the downstream end of the model until it is demonstrating proper behavior upstream from that point.

(2) Second, be sure the model is numerically stable before adjusting any coefficients or processes.

(3) Once the above two conditions are met, focus attention on overall model performance. Check the boundary conditions to ascertain that the particle size classes in the inflowing sediment load have been assigned "representative" concentrations. Use depth and gradation of the bed sediment reservoir to determine that the model bed matches the prototype. Make plots for several different times because the gradation of the model bed will vary with the inflowing water-sediment mixture. Correct any inconsistencies in these data and try another execution. If any problem persists, check the field data for possible rock outcroppings and check calculated profiles for possible errors in nearby sections.

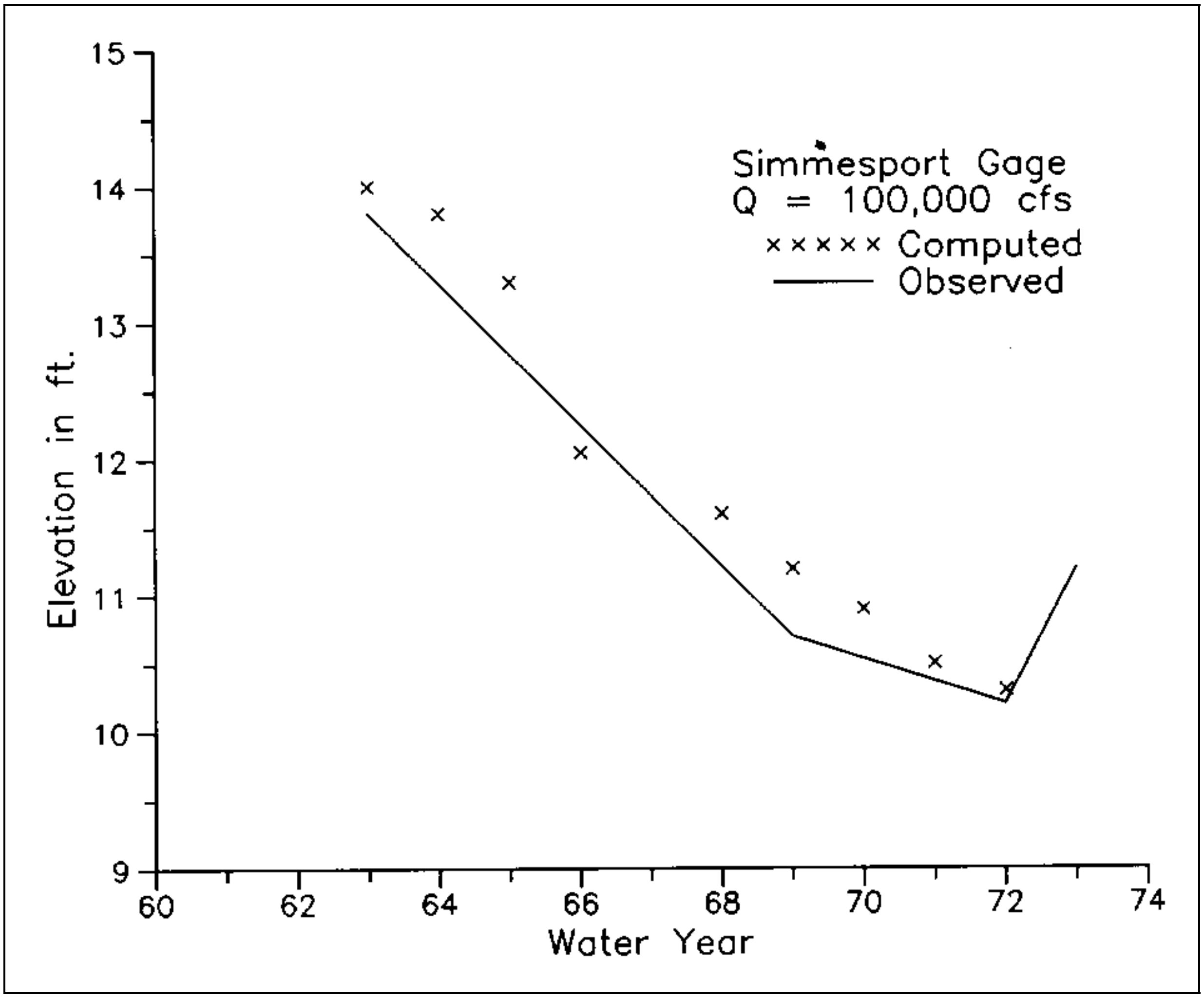

Figure 7-14. Water surface trend plot (specific gage plot)

(4) If calculated transport rates are too high, check prototype data for a gravel deposit which could be forming an armor layer.

(5) If calculated rates of deposition are too high or rates of erosion are too low, check top bank elevations and ineffective flow limits to ensure that the model is not allowing so much flow on the overbanks that the channel is becoming a sink.

(6) Finally, if none of the above actions produce acceptable performance, change the inflowing sediment load. First use a constant ratio to translate the curve without rotation. If that is not successful, rotate the curve within the scatter of data.

7-10. Development of Base Test and Analysis of Alternatives

The most appropriate use of a movable bed simulation is to compare an alternative plan of action with a base condition.

a. The base test. In most cases the base condition is the simulated behavior of the river under a "no action future." In a reservoir study, for example, the base test would calculate the behavior of the river, both upstream and downstream of the proposed dam site, without the dam in place. In many cases, the base test simulation should show little or no net scour or deposition. These are river reaches which are near equilibrium (where scour approximately equals deposition) under existing conditions.

b. Plan tests. The project alternatives can be simulated by modifying the base test data set appropriately. In the case of a reservoir, a dam can be simulated by inserting "operating rule data" into the base test model. For a channel improvement project, cross-sectional geometry and roughness can be changed. If a major change is to be analyzed, make the evaluation in steps. Avoid changing more than one parameter at a time because that makes the results difficult to interpret. For example, it is best to analyze a channel modification project in two steps. First, change the hydraulic roughness values and simulate future flows in the existing geometry. It will be necessary to select and justify the Manning's *n* for future conditions. Justify values by consideration of proposed design shapes, depths, channel lining materials, proposed vegetation on the overbanks, probable channel debris, anticipated riprap requirements, and maintenance agreements. Second, insert the modified cross sections and complete the analysis by simulating the alternatives to be tested. Also, select the appropriate contraction and expansion coefficients. Use model results as an aid in predicting future conditions; rely heavily on engineering judgment and look for anomalies in the calculated results. These "surprises" can be used by the experienced river engineer to locate data inadequacies and to better understand the behavior of the prototype system. Any unexpected response of the model should be justified very carefully before accepting the results.

c. Presentation of results. Results should be presented in terms of change from the base case wherever possible rather than absolute values. This will provide an assessment of the impacts of proposed projects.

d. Sensitivity tests. It is usually desirable during the course of a study to perform a sensitivity test. Quite often certain input data (such as inflowing sediment load) are not available, or subject to substantial measurement error. The impact of these uncertainties on model results can be studied by modifying the suspected input data by ± x percent and rerunning the simulation. If there is little change in the simulation, the uncertainty in the data is of no consequence. If large changes occur, however, the input data needs to be refined. Refinement should then proceed using good judgment and by modifying only one parameter or quantity at a time so as to be able to see the exact effect that overall changes may have. Sensitivity studies performed in this manner will provide sound insight into the prototype's behavior and lead to a sound model description of the real system.

Section V
Computer Programs

7-11. Introduction

Many computer programs are available for movable boundary simulations, and more will be created in the future. Two widely used programs are briefly discussed below as examples. This is not an exhaustive review. For any particular study, the need for use of a particular program or suite of programs must be defined and justified early in the study. See Chapter 3.

7-12. Scour and Deposition in Rivers and Reservoirs (HEC-6)

HEC-6 (U.S. Army Corps of Engineers 1991a) is a movable boundary model. It was formulated around Einstein's basic concepts of sediment transport; however, it is designed for the nonequilibrium case. Einstein did not address the nonequilibrium condition, but his "particle exchange" concept was extended in HEC-6 by noting that when sediment is in transport there will be a continual exchange between particles in motion and particles on the bed surface. The residue in the bed may be measurable, as in the case of the "bed material load", or it may be unmeasurable, as in the case of "wash load". The stability of particles on the bed surface may be related to inertia, as in the case of noncohesive particles; or that stability may be primarily electrochemical, as in the case of cohesive particles. Energy forces acting to entrain a particle may be primarily gravity induced, as in the case of flow in inland rivers; or the forces may be combinations of energy sources such as gravity, tides, waves, and density currents, as in the coastal zone. Different types of sediment require different entrainment functions depending upon the propensity of the sediment to change hydrodynamic and physical properties of the flow and upon the sensitivity of the sediment type to water temperature and chemistry.

a. Equations of flow. The equations for conservation of energy and water mass are simplified by eliminating the time derivative from the motion equation which leaves the gradually varied steady flow equation. It is solved using the standard step method for water surface profiles. The following terms are included:

$$\frac{\partial h}{\partial x} + \frac{\partial(\alpha U^2/2g)}{\partial x} = S_e \qquad \text{(conservation of energy)} \quad (7\text{-}2)$$

where

g = acceleration due to gravity
h = water surface elevation
S_e = slope of energy line
U = flow velocity
x = distance in the direction of flow
α = correction for transverse distribution of flow velocity

$$Q = UA + Q_1 \qquad \text{(conservation of water)} \quad (7\text{-}3)$$

where

A = cross-sectional area of flow
Q_1 = lateral or tributary inflow
Q = main stem water discharge downstream from Q_1
U = main stem mean water velocity upstream from Q_1

b. Friction and form losses. Both friction and form losses are included in S_e; bed roughness is prescribed with Manning n values. n values may vary with water discharge, location, or be related to bed material size (Limerinos 1970).

c. Equation of sediment continuity. The Exner equation is used for conservation of sediment:

$$\frac{\partial Q_s}{\partial x} + B_s \frac{\partial Y_s}{\partial t} + q_s = 0 \qquad \text{(conservation of sediment)} \quad (7\text{-}4)$$

where

B_s = width of bed sediment control volume
Q_s = volumetric sediment discharge rate
q_s = lateral or tributary sediment discharge rate
t = time
Y_s = bed surface elevation

d. Computational methodology. Descriptions of the computational methodology used in HEC-6 and application of the program are presented in HEC by the U.S. Army Corps of Engineers (1991a).

7-13. Open Channel Flow and Sedimentation (TABS-2)

a. Purpose. The purpose of the TABS-2 system (Thomas and McAnally 1985) is to provide a complete set of generalized computer programs for two-dimensional numerical modeling of open-channel flow, transport processes, and sedimentation. These processes are modeled to help analyze hydraulic engineering and environmental conditions in waterways. The system is designed to be used by engineers and scientists who need not be computer experts.

b. Description. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation processes in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure 7-15.

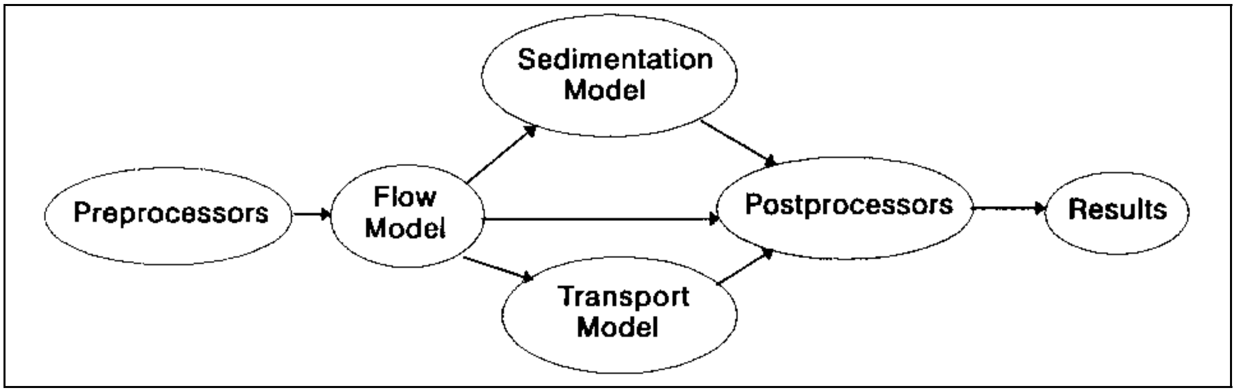

Figure 7-15. TABS-2 schematic

c. Uses. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, dispersive transport, sediment erosion, transport and deposition, resulting bed surface elevations, and feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact of project designs on flows, sedimentation, and salinity. The calculated velocity pattern around structures and islands is particularly useful. Some applications of TABS-2 are referenced in Chapter 3.